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## REACTIVE MOTION PLANNING FOR MOBILE CONTINUUM ARM IN DYNAMIC INDUSTRIAL ENVIRONMENT

AHMAD ATAKA\*, ALI SHIVA, AND ALI SHAFTI

*The Centre for Robotics Research (CoRe), Department of Informatics, Kings College  
London,*

*London WC2R 2LS, United Kingdom.*

*\*E-mail: [ahmad.ataka@kcl.ac.uk](mailto:ahmad.ataka@kcl.ac.uk)  
[www.kcl.ac.uk](http://www.kcl.ac.uk)*

HELGE WURDEMANN

*Department of Mechanical Engineering, University College London, Torrington Place,  
London WC1E 7JE, United Kingdom.*

*E-mail: [h.wurde mann@ucl.ac.uk](mailto:h.wurde mann@ucl.ac.uk)*

KASPAR ALTHOEFER

*School of Engineering and Material Science, Queen Mary University of London, Mile  
End Road,*

*London E1 4NS, United Kingdom.*

*E-mail: [k.althoefer@qmul.ac.uk](mailto:k.althoefer@qmul.ac.uk)*

Nowadays, rigid-link manipulators have been extensively used in various industrial applications, such as automotive industry and manufacturing operations. Nonetheless, despite of their precise and well-established position control, rigid-link manipulators suffer from their lack of flexibility, especially when operated in cluttered, unknown, dynamic environments, as well as their inherent rigidity which limits their applications in a shared human-robot workspace. In this paper, we report our current progress on mobile continuum manipulators application in dynamic environments. The results show that a continuum arm, mounted on a mobile platform and equipped with a reactive motion planner, is a promising candidate to be used in dynamic industrial environments.

**Keywords:** Reactive Motion Planning; Continuum Arm; Mobile Platform; Dynamic Environment.

## 1. Introduction

The rigid-link manipulators have been largely deployed in various industrial applications. Mainly characterized by their precise position control, rigid-link manipulators have become a perfect choice in industrial tasks which require accurate movement in a well-defined environment. Nonetheless, this feature does not eliminate the fact that current rigid-link manipulators suffer from lack of flexibility, especially when operated in cluttered, unknown, dynamic environments. Their inherent rigidity also limits their applications in a task which requires human and robot working together in a shared environment.

In the last decade, several works have attempted to improve safety aspect of rigid-link manipulators. Several attempts from the mechanical side have been reported, such as the design of flexible joint<sup>1</sup> and variable stiffness actuator.<sup>2</sup> Although these solutions are generally low cost and have fast response, they lack flexibility due to the fact that every task will need a special-purpose compliant design. From the control design side, several works have also been reported, such as a design of human-aware motion planning which tried to use the safety criteria as parameters in the motion planning stage<sup>3</sup> and an elastic strip algorithm which exploits redundancy of the manipulators.<sup>4,5</sup>

Besides those efforts, a recent development of new continuous backbone manipulators has been well presented in several works.<sup>6,7</sup> This continuum manipulators, due to their ability to bend at any point along the backbone, possess higher flexibility and dexterity compared to the rigid-link counterparts. Continuum manipulators are able to navigate in tight space and also manipulate object with their whole body. Their compliance structure also makes their performance better under unavoidable contact with environments, including human. Thus, despite their current vast deployment in medical applications,<sup>8</sup> continuum manipulators can be a promising candidate for industrial setting, like the serpentine-style manipulator used in waste storage tank remediation,<sup>9</sup> especially when attached on a mobile platform.

In this paper, we report our current research on the design of reactive motion planning strategy for mobile continuum manipulators in dynamic environments. The motion planning is a modification of a well-known potential field method usually employed in rigid-link manipulators. The algorithm was tested on a model of three-segments continuum manipulators assumed to be mounted on a mobile platform. The results show that the proposed system can reach a desired position while avoiding contact with

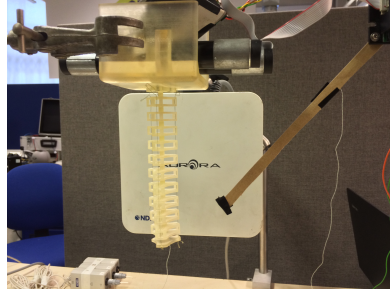


Fig. 1. An example of a tendon-driven continuum manipulator used as a model in this work.

moving obstacle and, thus, can be a promising candidate to be used in dynamic industrial setting, such as the one which requires human-robot coexistence and collaboration.

## 2. Mobile Continuum Manipulator Model

In this section, we summarize the mathematical model that we use throughout the paper. The continuum manipulator model is based on a constant-curvature kinematic model. Each segment of the manipulators is assumed to be a circular arc with constant curvature radius at every given time. The pose of each segment is described by three configuration space parameters, i.e. the arc curvature  $\kappa$ , deflection angle  $\phi$ , and segment length  $s$ . These parameters will determine the pose of the tip with respect to the base according to a forward kinematics relation as presented in.<sup>6</sup>

Besides the general forward kinematics relation which maps the configuration space to task space for all type of constant-curvature continuum manipulators, we also need a specific mapping from actuator space to the configuration space which depends on the actuation strategy of the manipulators. The model in this paper is based on a tendon-driven continuum manipulator presented in<sup>10</sup> as depicted in Figure 1. Every segment consists of 3 uniformly-separated tendons used to govern the movement. The  $N$ -segments manipulator with a movable base can be described by actuator space variables defined as  $\mathbf{q} = [\mathbf{q}_0 \ \mathbf{q}_1 \ \dots \ \mathbf{q}_N]^T$ . While  $\mathbf{q}_0 \in \mathbf{R}^6$  represents the base's position and orientation for a 6 degree-of-freedom base, every element  $\mathbf{q}_i$  for  $i > 0$  describes segment- $i$  where  $\mathbf{q}_i = [l_{i1} \ l_{i2} \ l_{i3}]^T$  and  $l_{ij}$  denotes the tendon's length of tendon- $j$  in segment- $i$ . The mapping between this actuator space variables to the configuration space variables is well documented in.<sup>6</sup>

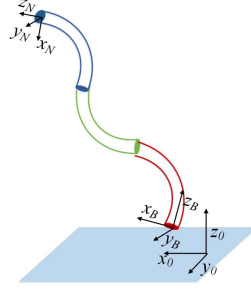


Fig. 2. This figure illustrates a three-segments continuum manipulator with mobile platform.

The pose of the point along the body of manipulators  $\mathbf{p}(\mathbf{q}, \xi) \in \mathbb{R}^3$ , including the special case end-effector, can be derived using the forward kinematics relation.  $\xi$  is defined as a scalar coefficient vector, describing a point along the body of segment- $i$  from the base ( $\xi_i = 0$ ) to the tip ( $\xi_i = 1$ ). The pose can be expressed as

$${}^0_N\mathbf{T}(\mathbf{q}, \xi) = \begin{bmatrix} \mathbf{R}(\mathbf{q}, \xi) & \mathbf{x}(\mathbf{q}, \xi) \\ \mathbf{0}_{1 \times 3} & 1 \end{bmatrix} \quad (1)$$

where  $\mathbf{R}(\mathbf{q}, \xi) \in SO(3)$  stands for the rotation matrix. Applying a partial derivative to the position vector with respect to actuator space variables  $\mathbf{q}$ , we can calculate the Jacobian  $\mathbf{J}(\mathbf{q}, \xi) \in \mathbb{R}^{3 \times 3N}$  which relates velocity in task space to the actuator space as follows

$$\dot{\mathbf{q}} = \mathbf{J}(\mathbf{q}, \xi)^+ \dot{\mathbf{x}}(\mathbf{q}, \xi), \quad (2)$$

where  $(^+)$  operation represents a pseudo-inverse as described in.<sup>11</sup>

### 3. Reactive Motion Planning

Due to the nature of the unpredictable environment, the motion planning strategy is based on a reactive obstacle avoidance approach. The well-known potential field<sup>12</sup> is employed in this paper with a modification such that it can be easily applied to a kinematic model of continuum manipulators. In preference to use the negative gradient of the potential ( $-\nabla U(\mathbf{x})$ ) as a task-space force  $\mathbf{F}$ , we use them as a task-space velocity input  $\dot{\mathbf{p}}$ . The attractive field is designed to attract the end-effector towards a desired point while the repulsive field is applied to a series of points-subjected-to-potential (PSPs) along the backbone of manipulator to make it avoid collision. The resulting

task space field can then be transformed to an actuator space velocity  $\dot{\mathbf{q}}$  via inverse Jacobian relation in Equation (2).

Besides the field for obstacle avoidance, we also add another layer of potential field in the actuator space for constraint avoidance. This is useful to avoid the inherent mechanical constraints in the continuum manipulators, i.e. the maximum and minimum tendon's length deviation from a normal length. This is done by applying an attractive field to make the tendon's length as close as possible to the normal length  $L$ , which consequently makes the tendon's length avoid maximum or minimum deviation. To make this added potential works with as less disturbance as possible to the task space obstacle avoidance potential, we multiply the overall constraint-avoidance term with a weight function which depends on a distance between the end effector  $\mathbf{x}$  and a target point  $\mathbf{x}_d$  as follows

$$w(\mathbf{x}) = (1 - e^{-\mu\|\mathbf{x}-\mathbf{x}_d\|}), \quad (3)$$

where  $\mu$  is positive constant.

The total field in actuator space can be derived by adding all of the field components from the obstacle avoidance stage, i.e. the attractive field in the end-effector and the repulsive field in all PSPs, as well as from the constraint-avoidance stage. A more detailed explanation on this reactive motion planning algorithm can be seen in.<sup>13</sup> This actuator space velocity  $\dot{\mathbf{q}}$  will be fed as an input to the kinematic model. In reality, this can be realized by modifying the tendon's length  $\mathbf{q}$  using DC motors connected to each tendons.

#### 4. Results and Discussion

In this section, we present the simulation results of the proposed algorithm. The simulation was built under Robot Operating System (ROS) architecture, running at a rate of 40 Hz. The number of segments is chosen to be 3 ( $N = 3$ ) and the number of PSPs is 3 per segment. The target is assumed to be fixed (drawn as a red point) while a spherical obstacle with the radius of 0.01 m (drawn as a black sphere) moves at a constant speed.

In Figure 3, we can see the movement of the manipulators when the obstacle moves close to the upper segment. We can see that the body of manipulators can modify its shape to avoid collision with the obstacle while, at the same time, the end effector still maintains its position to match a desired target. This flexibility is advantageous, especially if the industrial environment where the manipulator works is cluttered and unstructured.

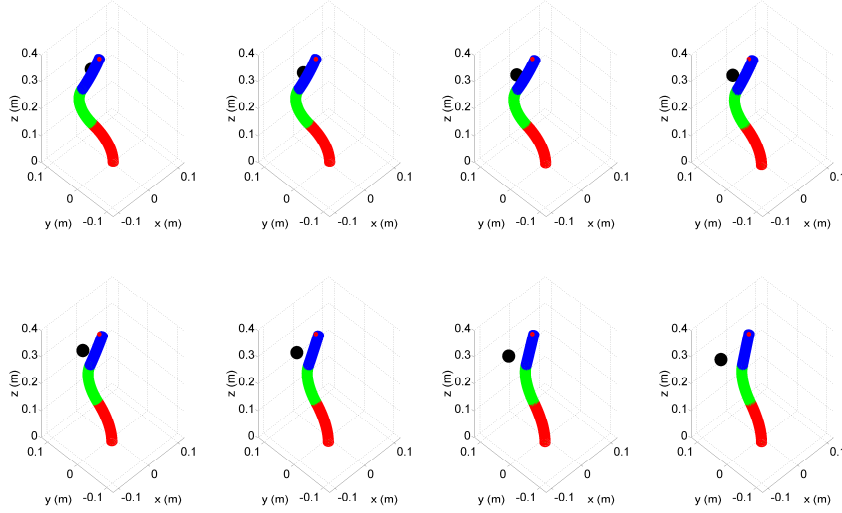


Fig. 3. The behavior of the manipulator for a static target position (small red dot) when obstacle (black sphere) moves close to the upper segment. The order of movement is as follows: upper left picture, upper right picture, lower left picture, and finally lower right picture.

Figure 4, on the other hand, demonstrates the movement of manipulator when obstacle moves close to the lower segment as well as the mobile platform. The redundancy makes the manipulator can avoid obstacle by changing the shape accordingly as well as moving its mobile base without disturbing the task, i.e. makes the end effector tracks a static target position.

From the results, we can see that the reactive manner of the algorithm, combined with inherent flexibility and compliance of the continuum manipulators, make the mobile continuum arm powerful for dynamic industrial environments. The obstacle avoidance will make the manipulators avoid collision by fully exploiting their redundancy and flexibility, hence, makes them well suited for dynamic and cluttered environments. In case of unavoidable contact with the environment, the inherent compliance also makes them safer in comparison to the rigid-link counterparts. These advantages of course do not eliminate the fact that the current continuum manipulators are still lacking in terms of force control and payload capacity, which are also among the important aspects in a number of industrial tasks. However, for a simple task, such as picking and placing light object, by attaching a

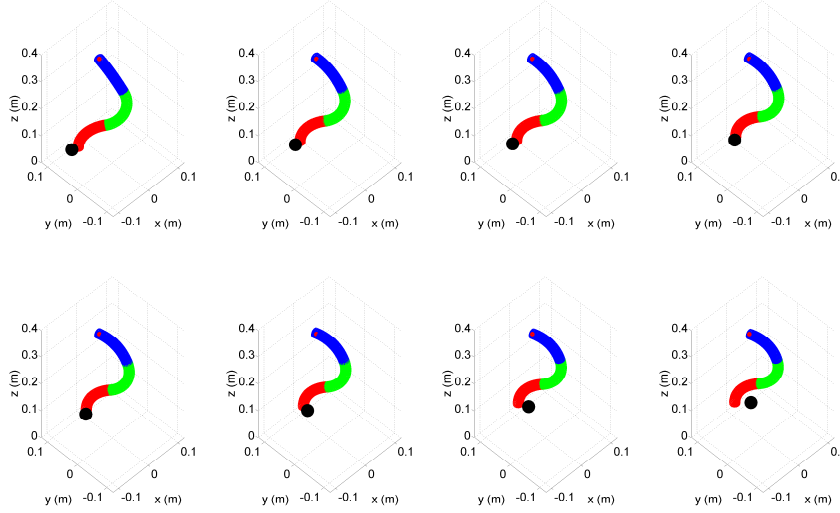


Fig. 4. The behavior of the manipulator for a static target position (small red dot) when obstacle (black sphere) moves close to the lower segment and the mobile platform. The order of movement is as follows: upper left picture, upper right picture, lower left picture, and finally lower right picture.

gripper in the end effector, this manipulator along with the algorithm will be perfectly fit.

## 5. Conclusions

In this paper, we present our recent progress on a reactive motion planning for multi-segment tendon-driven continuum manipulator with a mobile platform. The algorithm is based on a modification of a well-known potential field used to attract the end effector to a desired target and repel the manipulator's body from collision. Another layer of potential field is also used to avoid mechanical constraint in the manipulator during the movement. The algorithm is shown to work well in avoiding moving obstacle for the kinematic model of continuum manipulator. The work demonstrates that the overall proposal makes a suitable candidate to be applied in dynamic industrial settings, especially those that have cluttered environment or human worker close to the manipulator.

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